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Meteorological Analysis of the December 4–6 FIRE Cirrus-II Case

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1 Introduction

During the period 4–6 December 1991, three distinct and separate cirrus cloud systems were observed to move over the FIRE Cirrus-II field site at Coffeyville (COF) in southeastern Kansas (Figure 1). Meteorological analyses of the first and third events are presented here. These cases were well-sampled by the regional rawinsonde network, highly instrumented aircraft, and extensive ground-based remote sensors at COF. Our analyses are primarily based on the rawinsonde observations. Unfortunately, the intervening event was not well-observed by the regional rawinsonde network.

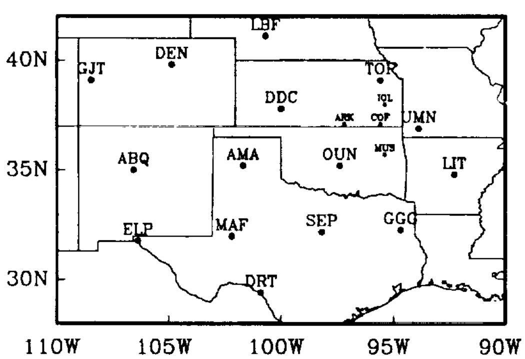


Figure 1: Map of rawinsonde stations located within the analysis region. Larger font indicates NWS stations, others are special FIRE CLASS stations.

Two large-scale synoptic features played a significant role in these cases. First, a closed-low circulation developed off the Baja coast on 4 December. This system drifted into the northern Gulf of California by the end of the period. This circulation pumped moisture to upper levels and resulted in extensive cirrus cloud formation over the southwestern U.S. in association with the leading ridge. Surges of upper level moisture and cirrus were also observed propagating northeastward across northern Mexico and southwestern Texas during this time period. Second, a persistent large-scale band of very dry air at middle and upper tropospheric levels, as evident on 6.7 μm GOES imagery, extended from the Great Basin eastward through central Kansas and into the southeastern U.S. As noted by Mace and Ackerman (1993), this feature was likely associated with a series of tropopause-fold events. Sassen (1992) speculated that aerosol-laden stratospheric air was brought down into the troposphere and undercut the moisture aloft.

2 Night of December 4–5 (0000–0900 UTC)

The first event occurred during the nighttime hours of 4–5 December 1991 and initially developed as a long thin cirrus band stretching in an anticyclonic arc from northeast New Mexico to COF. This cloud band appeared to propagate from an initial orographic forcing. Cirrus were first observed at COF by lidar after 0200 UTC. Significant cirrus development was later observed over Oklahoma on the south side of the cloud band. The event ended by about 1000 UTC as skies cleared. The 0600 UTC sounding from COF (Figure 2) showed relatively moist conditions at high levels with indications of two separate moist layers centered at about 10 and 11.5 km, respectively. Nominal sounding times are used here. Sampling at cirrus levels occurred $\sim 1/2$ hour prior to the nominal times in most cases. These moist layers were not evident at 0000 UTC though some indication of moistening was seen in the 0200 UTC sounding. By 1000 UTC, only a moist layer at about 9 km remained.

Analysis of the temporal evolution of the heights of isentropic surfaces at COF (Figure 2) indicates that the static stability was minimal in the upper moist layer when cloud development was strongest (0600 UTC). However, there was little evidence for convective instability in the lower moist layer in contrast to the lidar observations of very active convective development in this layer just after 0600 UTC. A very stable layer was observed below the region of cirrus cloud formation and lowered with time suggestive of an elevated warm frontal surface (~ 8 km at 0600 UTC).

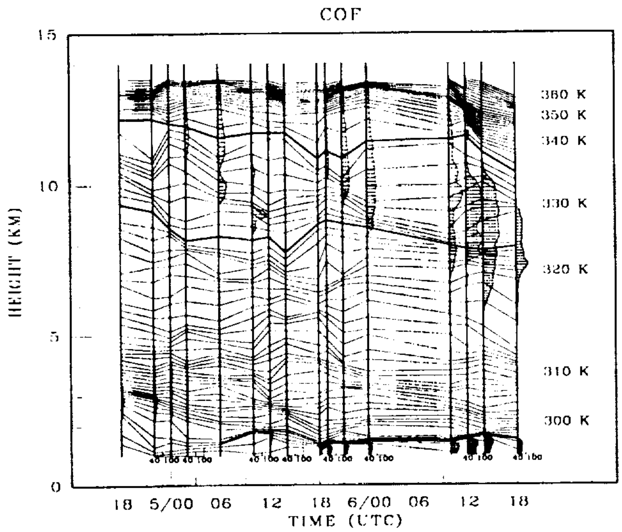


Figure 2: Time series of isentropic surfaces at 1 K intervals and percent relative humidity (shaded) as a function of height (km) from 1800 UTC on 4 December 1991 to 1800 UTC on 6 December 1991. The 325 K and 335 K isentropic surfaces are emphasized for comparison.

The 335 K isentropic surface cuts through the upper moist layer at COF, where high level cirrus occurred during this time period (Figure 2). Regional analysis of the geopotential height, horizontal wind, relative humidity, and vertical motion fields on this isentropic surface are shown in Figures 3 - 5 along with infrared satellite images for the same times. The vertical motions were derived from an objective analysis of the height and wind fields using the method of Starr and Wylie (1990). Estimated accuracy of this technique is generally about ± 2 cm sec^{-1}. Only data from NWS stations were used for these analyses.

At 0000 UTC, a large cloud shield extended into eastern Arizona from the upper level low, positioned west of Baja. A substantial area of cirrus was also observed over eastern New Mexico and western Texas (Figure 3). The analyzed relative humidity field (values exceeding 80%) corresponds well with the observed cloud pattern. The moisture pattern at higher levels was very similar. It must be noted that the humidity sensor in the SDD rawinsondes used at many of south-central and southwestern NWS stations are prone to becoming "stuck" once near-ice saturation is encountered in the upper troposphere. This was an unexpected finding. Occasional observations of very high values (supersaturation) can usually be attributed to this sensor problem; nonetheless, the analyzed humidity patterns appear qualitatively correct.

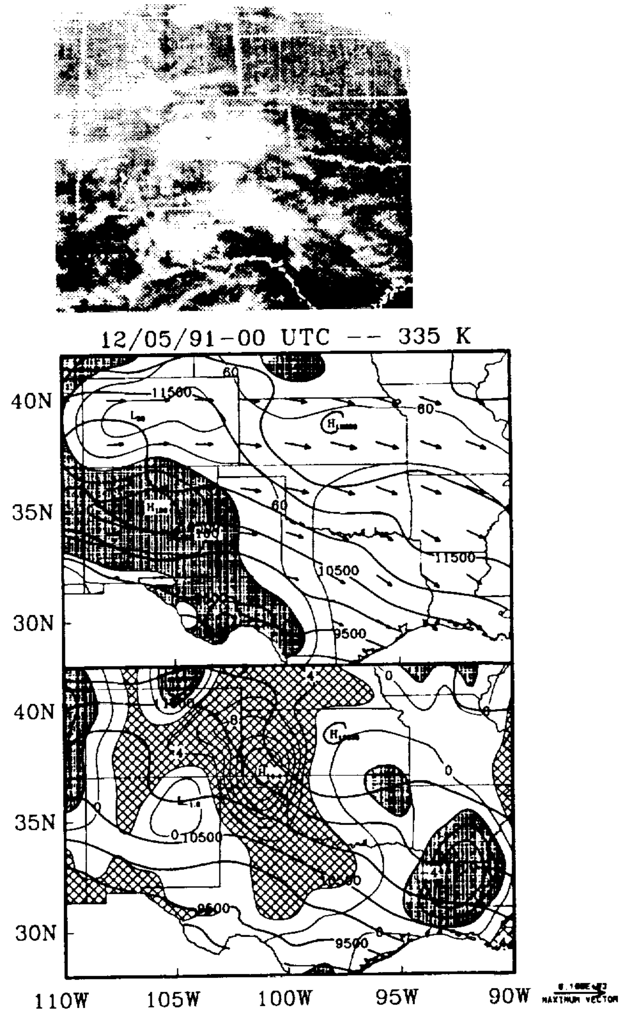


Figure 3: Infrared satellite imagery for 0000 UTC on 5 December 1991. Middle diagram shows lines of constant geopotential (thick solid) at 500 m intervals, percent relative humidity with respect to ice contoured at 20% intervals (thin solid), and wind vectors for the 335 K isentropic surface. Shaded regions indicate humidity levels exceeding 80%. The bottom diagram also shows lines of constant geopotential (thick solid), as well as vertical velocity (thin solid) contoured at 2 cm sec^{-1} intervals. Hatched regions indicate upward vertical velocities greater than 2 cm sec^{-1}, while shaded regions depict downward vertical velocities exceeding 2 cm sec^{-1}.

To the north over Colorado, significantly drier conditions were observed with relative humidity less than 40%. This dry region compares well with satellite imagery, where a noticeable swath of relatively cloud-free conditions was found. The northern 60% contour corresponds well with the northern boundary of the "dry" band observed in GOES water vapor channel (6.7 μm) imagery.

The vertical motion field shows a maximum of rising motion (14 cm sec^{-1}) located over the panhandle of Oklahoma along a north-south axis of rising motion. The axis of rising motion corresponds to the ridge axis evident in the cirrus cloud pattern, where upper level clouds appear densest. We often find that upper level moisture is maximized ahead of the axis of strongest upward vertical motion. Higher humidity is often observed ahead of strong upward motion because the air generally moves more rapidly than dynamical features. That the higher relative humidity observed over New Mexico lags the region of upward motion in this case likely indicates that the dynamical forcing responsible for that moistening actually occurred further to the west in association with the closed-low system. This case also illustrates that relatively strong upward motion, as found over eastern Colorado and western Kansas, is not necessarily associated with cloud formation. When the air is dry, an extended time may be required before the upward motion results in sufficient humidification. Subsidence was found over the eastern potions of Kansas, Oklahoma and Texas, where dry conditions (< 40%) and cirrus cloud dissipation were observed.

By 0600 on December 5, the cirrus cloud system had moved eastward extending from western Oklahoma into southern Missouri and Arkansas (Figure 4). Since only the 17 inner network NWS stations conducted launches at this time, the analysis area is considerably smaller. Relative humidity exceeded 80% over central Oklahoma in fair agreement with the satellite imagery although, as before, the apparently dissipating portion of the cloud field extended well into the drier air ahead. The center of maximum upward vertical velocity remained nearly constant in magnitude from the 0000 UTC analysis and moved southeastward to central Oklahoma, where it was located just on the southwestern side of the brightest cirrus clouds and just west of the ridge axis. It may also be seen that the band of high humidity extending southward into Texas now led the axis of strongest upward motion. Although relative humidity was high in the northwest portion of the analysis region, subsidence was diagnosed there consistent with the clearing seen in the satellite imagery. To the southeast, strong subsidence and drying were associated with cloud dissipation.

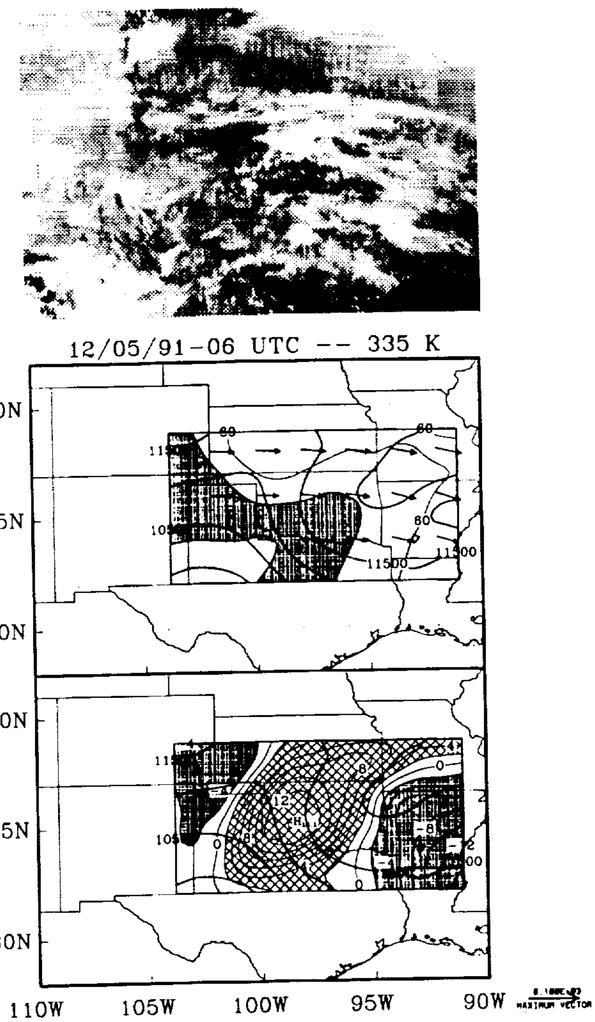
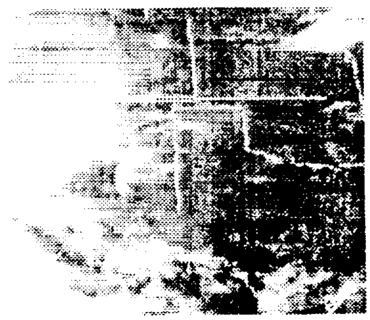


Figure 4: Same as in Figure 3 except at 0600 UTC.

The cirrus cloud system continued its rapid progression eastward and was situated over Arkansas by 1200 UTC on December 5 (Figure 5). Relative humidity exceeded 80% over western Texas, New Mexico, and southern Colorado in advance of an approaching band of strong upward motion. Subsidence was found in the lee side of the Rockies, where strong clearing and declining humidity were observed. The phasing of the upper level humidity and vertical motion fields were now more typical. Analyzed upward motions associated with the observed cirrus cloud system had moved eastward and diminished considerably (to $\sim$ 5 cm sec^{-1}) from the previous two analysis times.



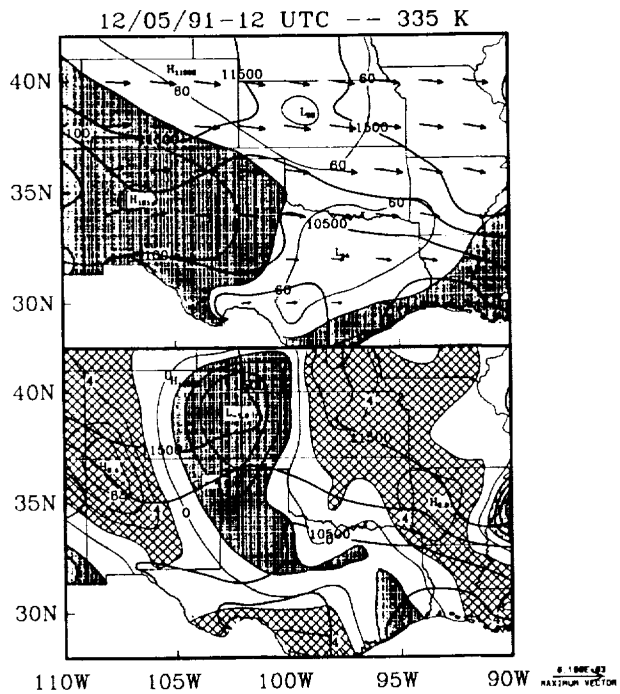


Figure 5: Same as in Figure 3 except at 1200 UTC.

Throughout this time period, two distinct layers (usually occurring together) of cirrus clouds were noted by lidar. The lower layer was initially observed around 9.5–10 km but progressively lowered and deepened to a height of 8.5–9.5 km. The upper layer extended from 10.5 km to 12.5 km or more with precipitation streamers occasionally reaching the lower cirrus layer. A time series plot of vertical motion analyzed for the Arkansas–Coffeyville–Muskogee (ARK–COF–MUS) triangle of special FIRE rawinsonde stations (Figure 1) is shown in Figure 6. Two distinct layers of weak upward vertical motion are evident at 0600 UTC and correspond very well with the observed cloud heights. Very weak upward motion was found from 8.5–9.5 km with somewhat stronger ascent from 11.0–13.0 km at 0600 UTC. Later at 1200 UTC, significant upward motions continue to be found in agreement with the analysis of NWS soundings shown in Figure 5. Thus, it appears that dry air rather than lack of upward motion caused the cessation of cirrus cloud formation over COF.

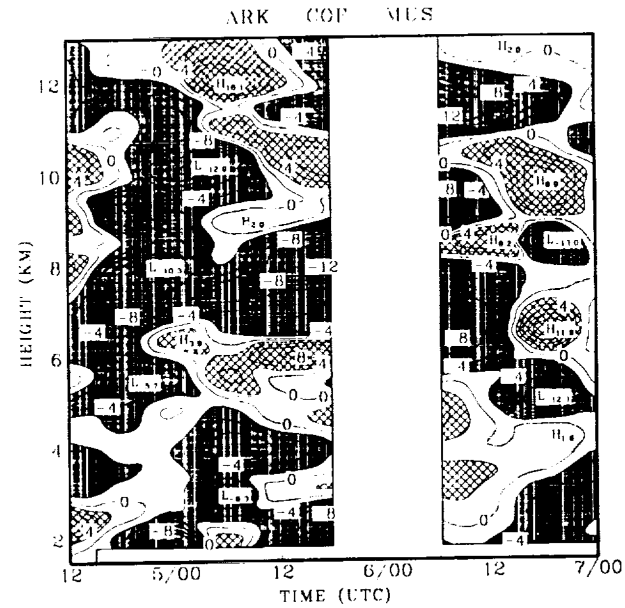


Figure 6: Contours of vertical motion for the triangle Arkansas – Coffeyville – Muskogee (ARK-COF-MUS) as a function of height (km) from 1200 UTC on 4 December 1991 to 0000 UTC on 7 December 1991. Contouring interval is 2 cm sec^{-1}. Hatched regions indicate upward vertical velocities exceeding 2 cm sec^{-1}, while shaded regions indicate downward vertical velocities greater than 2 cm sec^{-1}.

3 Morning of December 6 (1200–1800 UTC)

The third cirrus event occurred during the morning hours of 6 December 1991. Satellite imagery at 1230 UTC (Figure 7) shows cirrus associated with the subtropical jet stream covering southeastern Texas. Cirrus clouds are also found in central Oklahoma, eastern Kansas and central Missouri in association with a weak ridge-crest extending from western Oklahoma to southwestern Iowa.

Rawinsonde soundings from COF (Figure 2) show humid conditions over a fairly deep region of the upper troposphere (7–10 km) between 1000 and 1500 UTC on 6 December. By 1800 UTC, humidities had declined although somewhat moist conditions were still observed in the 7–9 km layer. Two other features are particularly noteable in the COF soundings. There is a rapid decline in tropopause height after 1200 UTC and a very stable layer was observed in the lower portion of the humid layer. This latter feature was continuously defined from the prior day and progressively lowered with time. As in the first case discussed here, this is highly suggestive of an elevated warm frontal surface.

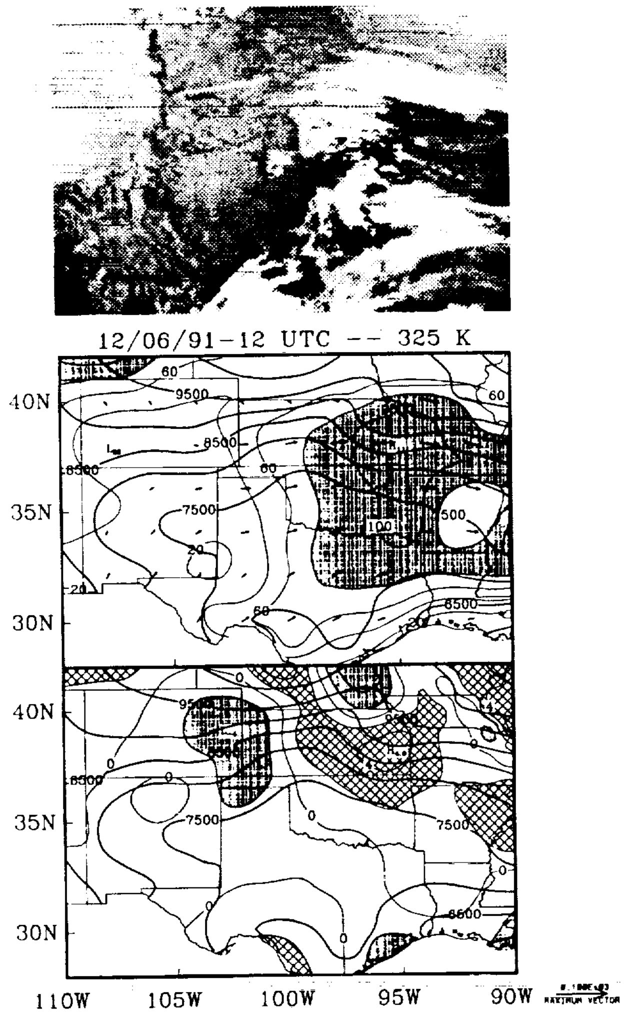


Figure 7: Infrared satellite imagery for 1230 UTC on 6 December 1991 (analysis is for 1200 UTC). Middle diagram shows lines of constant geopotential (thick solid) at 500 m intervals, percent relative humidity with respect to ice contoured at 20% intervals (thin solid), and wind vectors for the 325 K isentropic surface. Shaded regions indicate humidity levels exceeding 80%. The bottom diagram also shows lines of constant geopotential (thick solid), as well as vertical velocity (thin solid) contoured at 2 cm sec^{-1} intervals. Hatched regions indicate upward vertical velocities greater than 2 cm sec^{-1}, while shaded regions depict downward vertical velocities exceeding 2 cm sec^{-1}.

Aircraft and lidar observation indicated cirrus initially extended from between 9.5 and 10 km down to below 6 km. The cloudy region below 7.0 km was probably the result of ice crystal fallout from above. Generating cells were observed at upper levels. The lidar observations showed multi-layered structure although aircraft observers reported cloud at all internal flight levels. Some lowering of cloud top was noted during the mission although cloud top was apparently ill-defined. Cirrus rapidly dissipated after 1700 UTC.

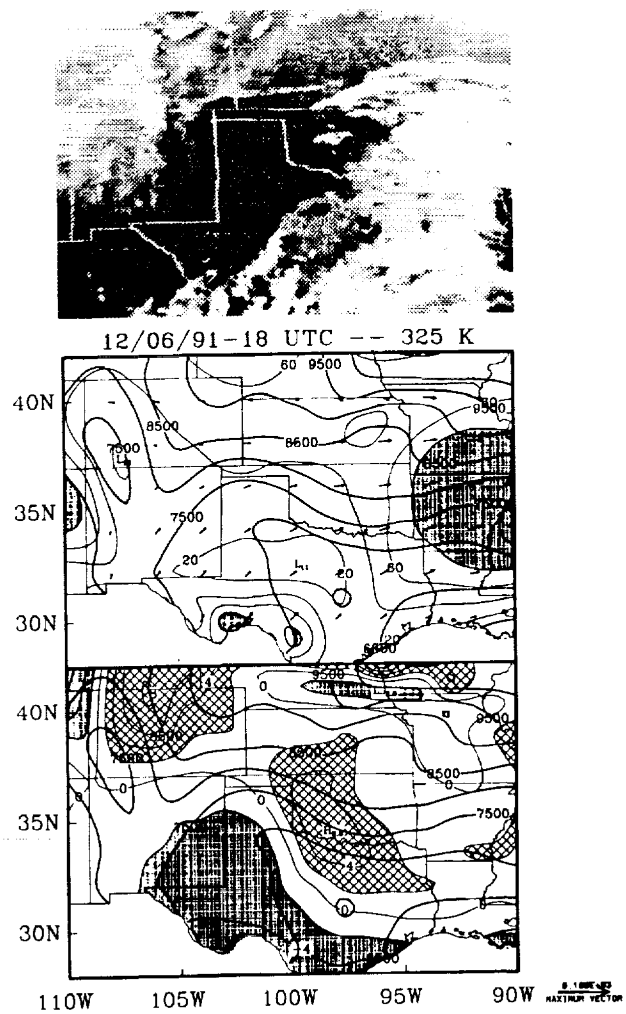


Figure 8: Same as in Figure 7 except satellite imagery and analysis are valid for 1700 UTC and 1800 UTC, respectively.

Analysis of the 325 K isentropic surface are presented for this case which corresponds to a height of about 8 km at COF (Figure 2). At 1200 UTC, relative humidity exceeded 80% over a fairly broad region to the east of the ridge axis lying through central

Kansas and western Oklahoma (Figure 7). The region of high humidity is also a region of weak upward motion. Strongest ascent (~ 4 cm sec^{-1}) in southeastern Kansas is well-correlated with the brightest and thickest part of the cirrus cloud system. To the north and west, subsidence was diagnosed, where clear regions were observed in the satellite imagery.

By midday, the cirrus cloud system and its associated region of high humidity had moved eastward (Figure 8) with the ridge axis. Vertical motion ahead of the ridge axis had declined to about zero. This is consistent with the observed dissipation of cirrus after about 1700 UTC. However, moderate upward vertical motion was now diagnosed in western Oklahoma in conjunction with the next approaching ridge crest. Lack of upper level moisture precluded formation of cirrus there.

4 Conclusions

Analysis of synoptic scale rawinsonde data for two of three cirrus events on 4–6 December 1991 revealed excellent correspondence between the satellite observed cloud patterns and the observed humidity and diagnosed vertical motion patterns. Upward motion from 4 to 14 cm sec^{-1} was found in association with upper level humidification and cirrus cloud formation. Highest humidity was generally observed ahead of the axis of strongest upward motion although this alignment took some time to develop in the first event. In each event, the cirrus clouds were associated with a weak shortwave ridge embedded in a generally westerly flow, i.e., ridge-crest cirrus (Starr and Wylie 1990). Analysis of data from the FIRE ARK-COF-MUS mesoscale station array was generally consistent with the larger scale results and with the vertical location of the cloud layers observed around COF. Overall, a tendency for low static stability was observed at COF in association with cirrus cloud development. An underlying stable feature resembling an elevated warm front was also observed in both cases as was a lowering of the tropopause height during each case, dramatically in the third event. A regional analysis was not possible for the intervening second event due to the lack of observations.

One conclusion that may be drawn from our analysis is that the sharp northern boundary of the ridge-crest cirrus was not found to be associated with a distinct dynamical boundary in these results. Rather, this feature appears to correspond to a transition from "humid-enough" to "not humid-enough" in the moisture field since upward motion features tend to straddle the cloud boundary in these cases, i.e., moderate upward motion was diagnosed in dry air where cloud formation was precluded. Here, the dry air was likely the result of prior tropopause-fold events (Mace and Ackerman 1993). Other areas of upward motion in dry air without cloud formation were also observed. However, we cannot eliminate the possibility of the existence of some narrow mesoscale dynamical feature that may not have been captured by the observations used here.

Lastly, the humidity sensor on the SDD sonde used by NWS stations in the south-central and southwestern U.S. has been frequently observed to "stick" once near-ice-saturation is encountered in the upper tropopause. This sometimes results in apparent observations of highly ice-supersaturated conditions at higher levels, even extending into the lower stratosphere in some cases.

5 Acknowledgments

The authors wish to thank Gerald Mace (Penn State University) and Ken Sassen (University of Utah) for valuable discussions regarding this case study and for providing access to satellite imagery (GM) and lidar observations (KS).

6 References

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